Technology for the Detection of Near Earth Objects

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Introduction

Since the launch of Sputnik in 1957, the Department of Defense (DOD) has invested considerable effort developing the technology and operational techniques required to conduct surveillance of earth orbiting objects. One major thrust of the DOD effort has been the development of techniques needed to discover and maintain a catalog of all manmade objects, with sizes above approximately 10 cm., in earth orbit. The technology and techniques that have allowed Space Command to populate and maintain such a catalog for over 30 years are applicable to the current issue of discovering and maintaining a catalog of natural objects that have the potential of impacting the earth. This paper examines the current generation of detector technology being infused into the operational space surveillance network, and predicts the performance of such systems when applied to the detection of natural Near-Earth Objects (NEOs). The predicted performance is then compared with the performance calculated for the proposed Spaceguard Survey system consisting of a network of 6 2.5 meter telescopes (Ref. 1).

Currently the United States maintains a world wide network of ground-based sensors used to develop and update the ephemeridies of all manmade objects in orbit around the earth. These sensors include both radars and passive electro-optic sensors. The sensor system of most interest for the detection of NEOs is the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system. Each GEODSS site has a complement of 40-inch main telescopes, currently equipped with Ebsicon detector systems. The GEODSS were designed to conduct wide area searches for high altitude satellites and as such have many of the features required to conduct NEO searches. Considerably improved detection performance will be achieved when the detectors are replaced with solid state Charge-Couple Devices (CCDs) under an ongoing upgrade program discussed in the next section.

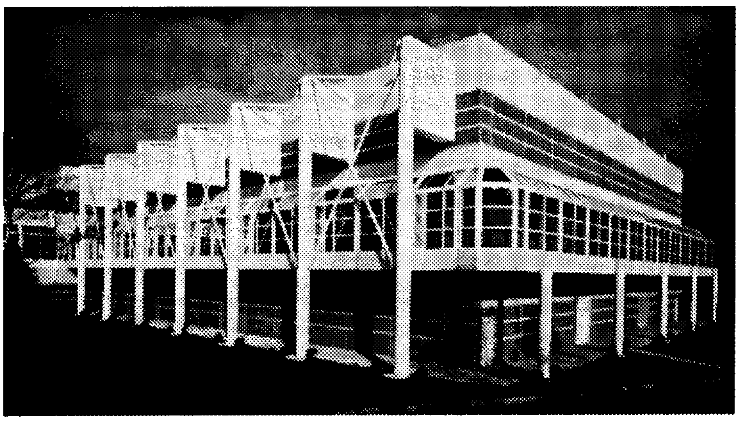
Lincoln Laboratory Focal Plane Technology

In support of the DOD, Lincoln Laboratory has developed a series of progressively more capable visible wavelength CCD focal planes. The CCDs are currently fabricated in the facility shown in Figure 1. The Lincoln Microelectronics Laboratory is a class 10 clean room facility which is capable of fabricating devices with features smaller than .25 microns. As shown in Figure 2, the first CCDs, developed in 1977, had 40,000 elements and readout noise of about 50 electrons at a readout rate of 0.5 Mpixels/sec. In order to support larger fields of view, successive generations of the CCDs were constructed with more pixels and were abuttable to allow large focal plane arrays to be built by constructing a gap free mosaic of several CCDs. As the fabrication process improved, the readout noise of the CCDs declined as well. The current generation, 1960X2560 pixel, CCD has noise performance better than 3 electrons at 1 Mpixel per second readout rates. In addition, the CCDs have been fabricated to be largely blemish free, containing very few bad columns or pixels.

Figure 3 shows the detail of the current generation 1960X2560 pixel CCD. The focal plane is equipped with 8 parallel readout ports to allow the 5 million pixel values to be readout in about 0.3 seconds. In contrast to most large format CCDs now on the market, which read directly out of the image array into the output port, the Lincoln Laboratory CCD is equipped with frame store buffers. These buffers are used to store the image outside of the active area for the duration of the readout. This feature eliminates the need for a mechanical shutter to define the exposure because the image is transferred from the image area into the frame buffer in about a millisecond. As soon as the image is transferred out of the active area a new integration may begin. The frame store locations are identified in Figure 3.

The sensitivity of the Lincoln Laboratory CCDs is enhanced by the very high quantum efficiency achieved over a broad wavelength band. As shown in Figure 4, when the CCD is appropriately anti-reflection coated the quantum efficiency exceeds 90% at peak and is above 20% across the entire interval between 400 nm. and 1000 nm. The optical response uniformity of the CCD is also quite good as shown in Figure 5. In the visible range the uniformity is better than 2% with degradation to about 10% into the near IR band.

LINCOLN MICROELECTRONICS LABORATORY



PROCESS CAPABLITIES

- 0.6 μm, LOW POWER, BULK CMOS
- MEGAPIXEL CCD IMAGERS
- FLAT PANEL DISPLAYS IN SOI CMOS
- 0.25 μm SOI CMOS (Development)
- FUSES AND ANTIFUSES
- 0.25 μm VERTICAL DEVICES
- PROGRAMMABLE MULTICHIP MODULES
- SUPERCONDUCTING CIRCUITS

- 8100 ft^2 CLASS 10
- PRODUCTION-CLASS 0.6 μm CMOS TOOLSET
  - ANGLED ION IMPLANTATION
  - CLUSTER METALLIZATION
  - CHEM-MECHANICAL PLANARIZATION
  - DRY ETCH
- UNIQUE 0.25 μm OPTICAL LITHOGRAPHY

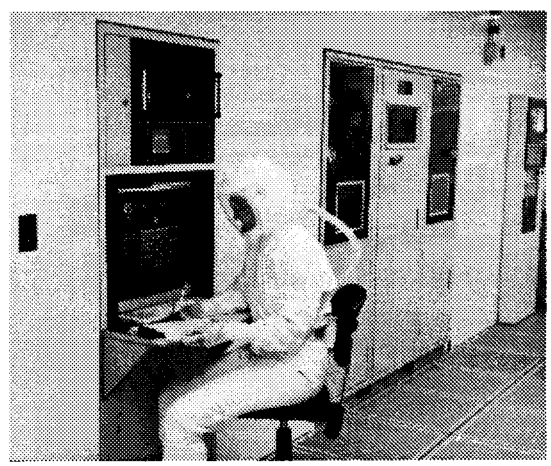


Figure 1. Lincoln Laboratory Microelectronics Laboratory.

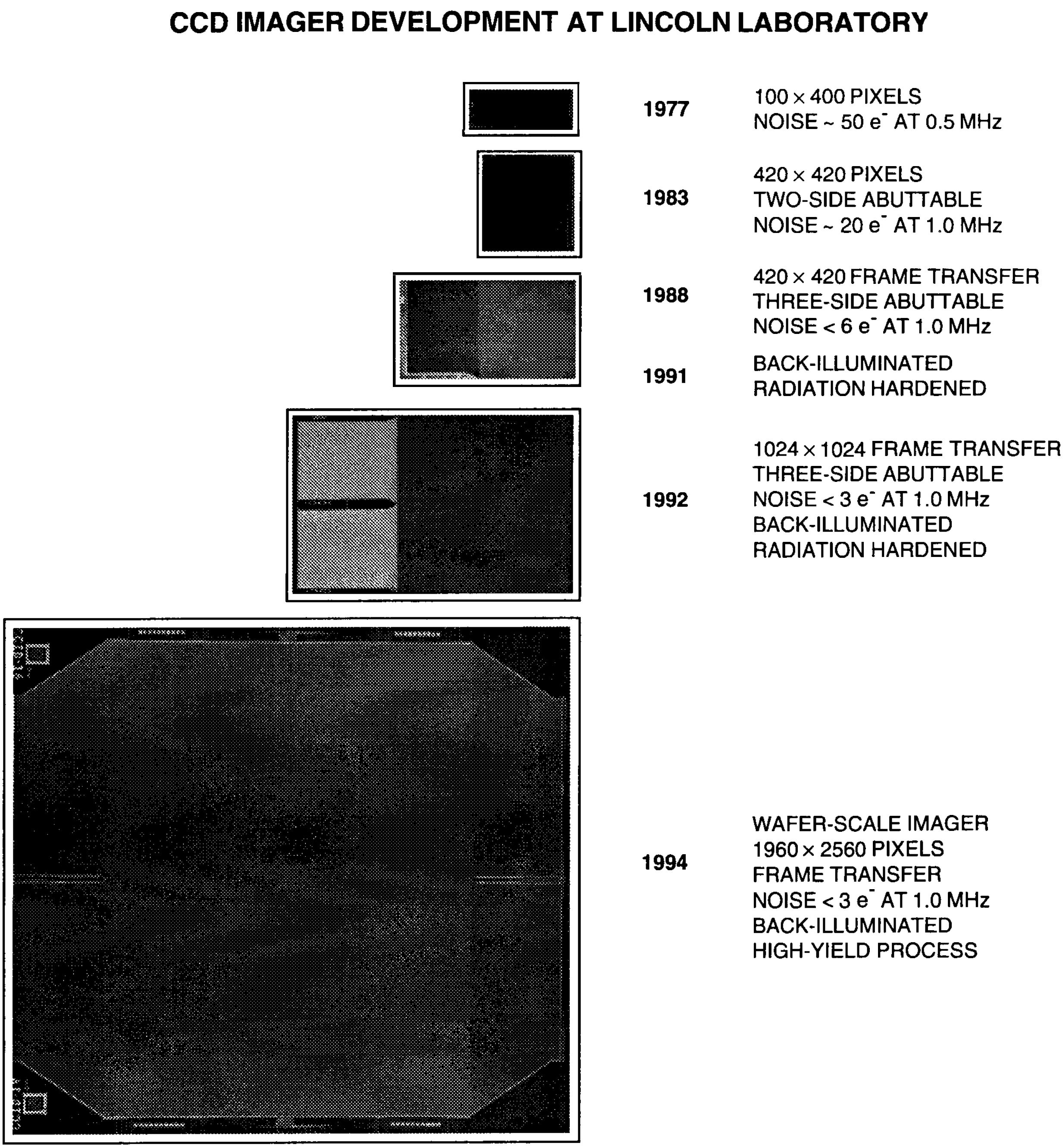


Figure 2. Five generations of visible CCD devices developed at Lincoln Laboratory for DOD applications.

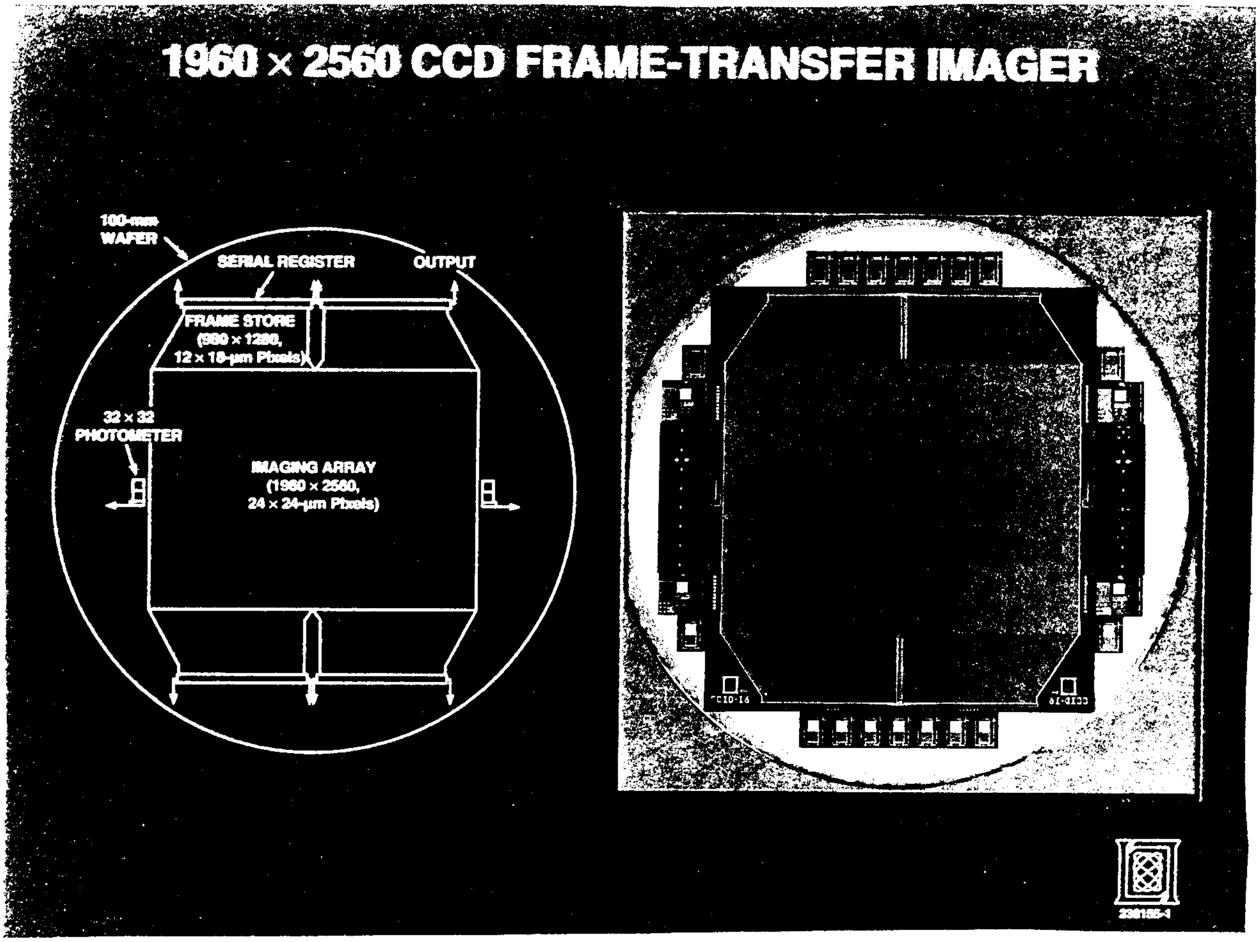


Figure 3. Detail of 1960X2560 pixel CCD showing output ports and frame storage locations.

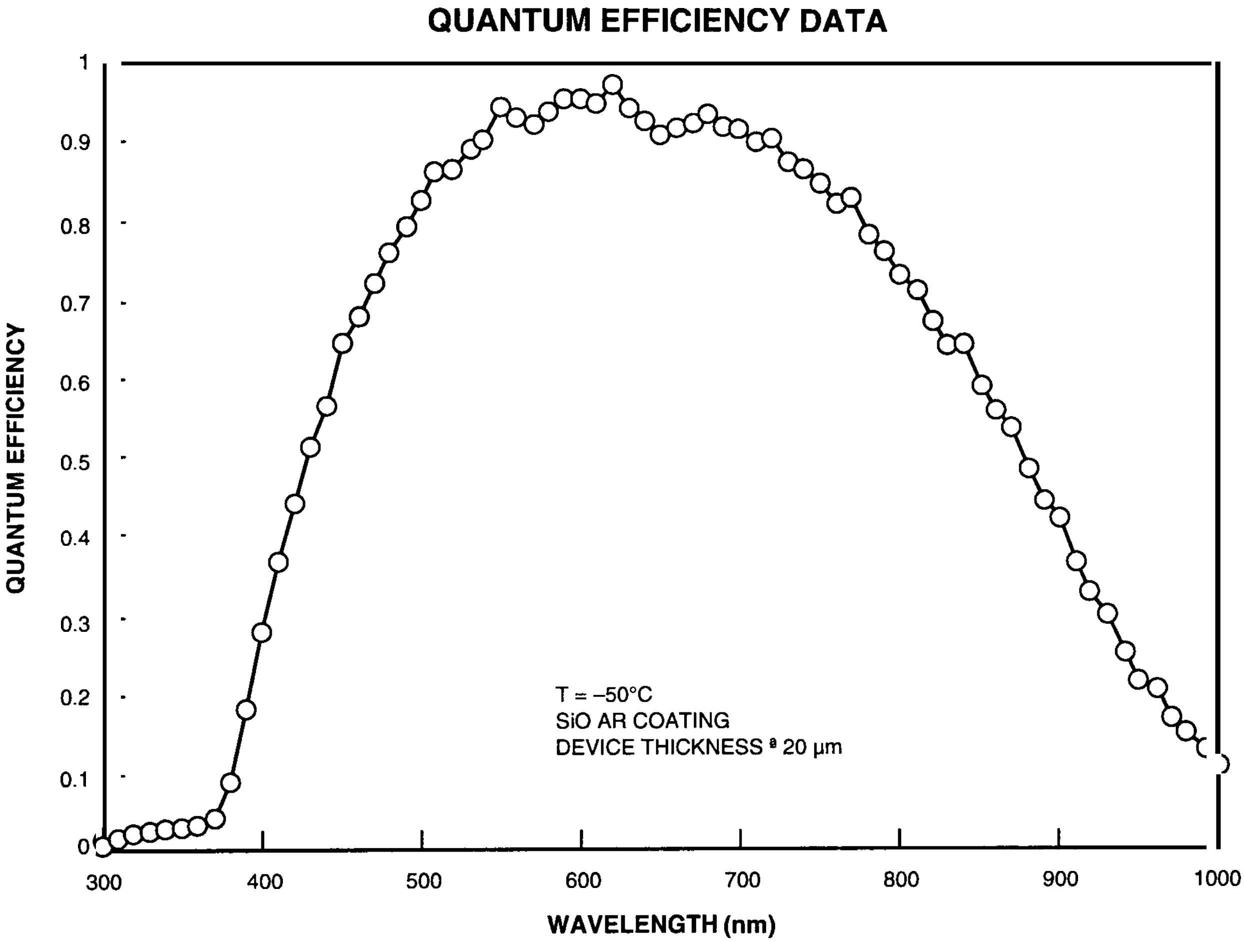


Figure 4. Quantum efficiency and a function of wavelength for anti-reflection coated 1960X2560 pixel Lincoln CCD.

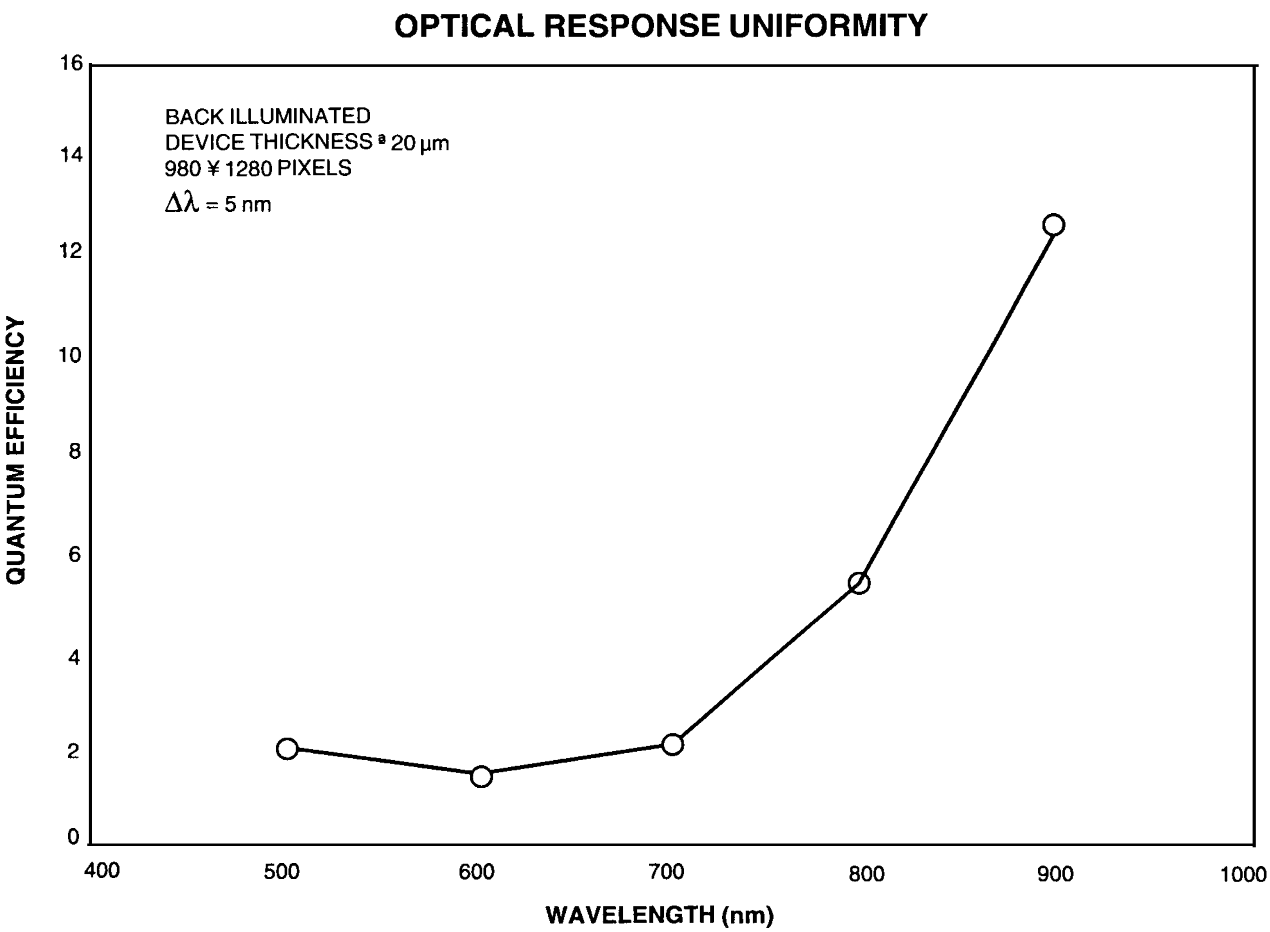


Figure 5. Optical response uniformity of the current generation Lincoln CCDs.

Another feature of interest for the detection of NEO's is the deep well capacity of the CCD. This allows long integrations to be accomplished before the dark current fills the well. The Lincoln Laboratory CCD has a well capacity of 200,000 electrons per pixel. For comparison, when the CCD is cooled to -50 degrees Centigrade, the dark current per pixel is approximately 10.5 electrons per second. That means that the dark current alone will take several hours to fill the well capacity.

The extremely fine angular resolution afforded by the large number of pixels is demonstrated by Figure 6. The picture, taken by the 1960X2560 pixel CCD, shows a house standing on Lexington Green since the Revolutionary War days. There is enough resolution in the picture to enlarge the sign on the front of the house and read the story of a Lexington Minuteman wounded at the Green who dragged himself home to die in the doorway at his wife's feet.

The CCDs described above have been constructed specifically to allow large portions of the sky to be searched to find dim, moving targets. As such, they have the best combination of large format and detection performance of any CCDs that exist today.

GEODSS System

The GEODSS system was deployed in the early 1980s by Space Command to conduct world wide electro-optic surveillance of deep space objects (deep space object in the Space Command parlance refers to any manmade satellite with an orbital period longer than 255 minutes). Reference 2 describes the details of the GEODSS system. The GEODSS were conceived as search sites capable of searching significant fractions of the geosynchronous belt in a night. As such, each site was equipped with three, agile, wide field-of-view telescopes. The main telescopes have 40-inch primary mirrors and a field of view of 2.1 degrees.

Using the current Ebsicon detector, the GEODSS system specifications require it to be capable of detecting satellites with a limiting magnitude of 16 when integrating for 0.6 seconds with a 19.5 magnitude sky background. This capability is not sufficient for productive NEO searches. However, the GEODSS telescopes, when combined with the large format CCD cameras discussed in the preceding section will have considerable NEO search capability as discussed in the next section.

Asteroid Detection Capability

The CCD detector and GEODSS telescopes discussed in the preceding sections have been designed to detect moving objects in space. While they have been specifically developed to detect satellites in earth orbit, they are also well suited to the detection of natural objects in heliocentric orbits. When compared with manmade satellites, asteroids and comets are generally seen moving more slowly, in the range from 0.1 to a few degrees/day, and are several magnitudes less bright. Appropriate modification of the integration times and velocity filters/detection algorithms employed to detect satellites will allow sensors based on these technologies to detect NEOs with quite good performance.

In order to have a basis for evaluating the performance of a GEODSS-based NEO detection system, some standard of comparison must be established. The defacto standard in the NEO community is the proposed Spaceguard system. The Spaceguard Study (Ref. 1), concluded in 1992, proposed the deployment of a system of six 2.5 meter telescopes each fitted with a commercial 2048X2048 CCD detector. Such a system is expected to be able to search 6000 square degrees of sky each month to a limiting magnitude of 22. In addition, the telescopes would conduct follow-up observations to develop and maintain a catalog of NEOs. The proposed system is estimated to achieve detection of 90% of the earth threatening objects, larger than 1 km in diameter, in 25 years of operation. Such a system was estimated to cost $50M (FY93) to construct and $ 10M per year to operate.

The specific measures of interest to our analysis of the GEODSS system capability is the Spaceguard goal of searching 6000 square degrees per month to a limiting magnitude of 22. This establishes a convenient basis on which to compare the capabilities of search systems.

The sensitivity of a system consisting of a Lincoln Laboratory CCD mounted on a GEODSS telescope is shown in Figure 7. The graph indicates the limiting magnitude (for SNR=4) achieved as a function of integration time. The top line indicates the performance expected in the absence of the moon, while the lower line indicates the performance for periods of full moon with the sensor looking 45 degrees away from the moon. The parameters used in the estimate of the performance are provided in the figure. As is indicated in Figure 7, on dark nights the system is capable of detecting objects with a visual magnitude of 22 with less than 100 seconds of integration.

HIGH SPATIAL RESOLUTION ACHIEVED BY 1960 × 2560 PIXEL CCD

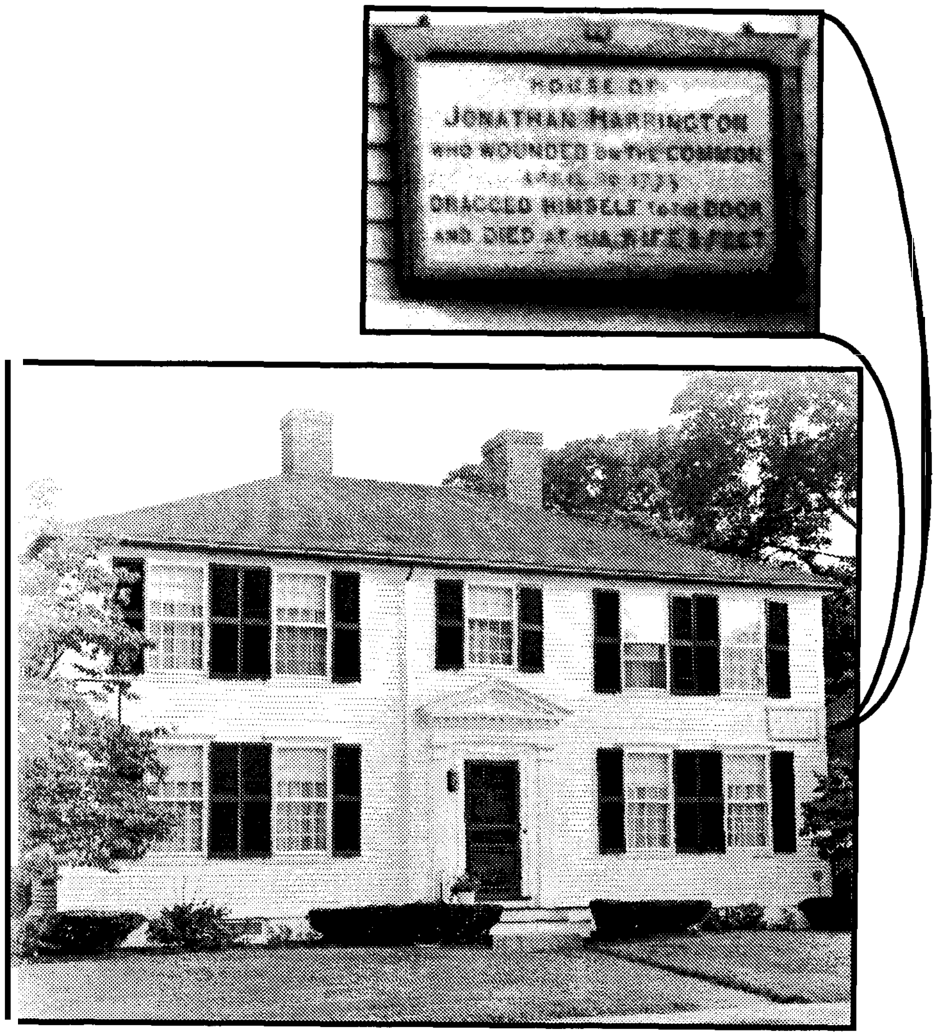


Figure 6 - Image of house on Lexington Green demonstrating the high spatial resolution achieved by the 1960X2560 pixel CCD.

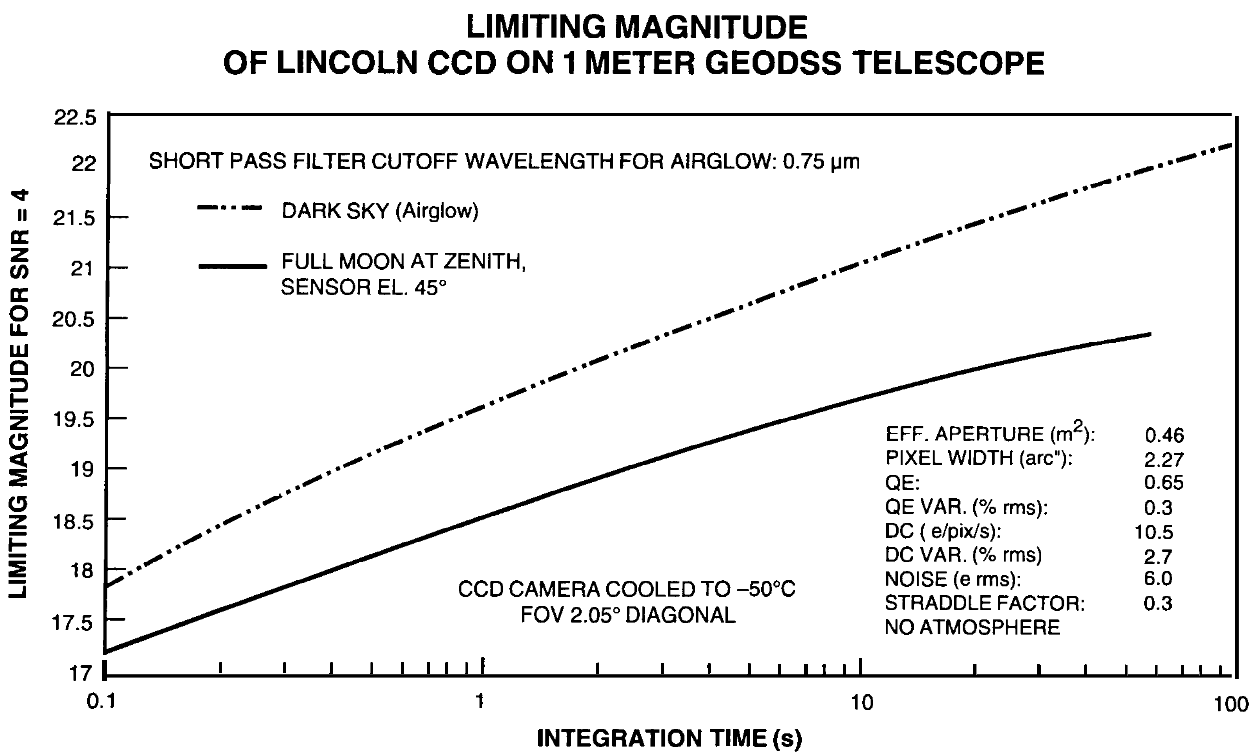


Figure 7. Limiting magnitude achievable using Lincoln CCD detectors on a GEODSS main telescope as a function of integration time.

Figures 8 and 9 give a feeling for what this detection performance means when applied to the detection of asteroids. Figure 8 (derived from Ref 1) provides the spectral characteristics for various classes of asteroids. This combined with the detection performance shown in Figure 7, yields the minimum diameter asteroid that the GEODSS/CCD system can detect at a distance of 1 AU. As shown in Figure 9, the minimum diameter is between about 100 meters and 300 meters depending on the asteroid's spectral class. Figure 9 also shows the effect of changing the short pass cutoff filter wavelength. The short pass cut off filter is used to remove the short wavelength light scattered by the atmosphere.

The limiting magnitude versus integration time, along with the other characteristics of the GEODSS telescopes has been combined in Figure 10 to indicate the search rate which could be accomplished by the GEODSS/CCD system as a function of limiting magnitude. The figure indicates the search rate for a system of either one or two GEODSS main telescopes and assumes three integrations will be needed for each field of view to detect the moving targets. The analysis assumes that the observing site will provide 1000 hours/year of good observing conditions. Under these conditions, a system consisting of a single telescope is capable of searching about 1500 square degrees per month to a limiting magnitude of 22. This analysis would indicate that 4 of the 1 meter GEODSS telescopes equipped with the Lincoln Laboratory CCD detector could search the 6000 square degrees per month as outlined in the Spaceguard Study.

Figure 10 also indicates that a system consisting of two telescopes could search the equivalent of the entire sky each month to a limiting magnitude of greater than 20.5. A search that covered the entire sky each month could be effective at finding smaller nearby objects which move faster and would likely have a higher initial discovery rate than deep searches covering smaller portions of the sky.

Lincoln Laboratory Field Tests

Lincoln Laboratory has conducted a series of field tests to demonstrate and validate the performance of the detector systems for space surveillance applications. These field tests have generally been focused on applications involving manmade satellites but, some data on natural objects has been collected. A discussion of the test series and the results obtained has been published in Ref. 3. This discussion will provide a top level overview of the historical test efforts and will describe an upcoming series which will test the latest large format CCD in a GEODSS telescope.

The historical tests of the CCD detector systems have been conducted using the facilities of the Lincoln Laboratory Experimental Test System (ETS) site located on the White Sands Missile Range near Socorro, New Mexico. The ETS is the prototype for the GEODSS systems. The primary telescopes at the ETS are the 31-inch polar mount Cassegrain telescopes shown in Figure 11. In September 1992 tests were conducted at ETS using a 420X420 pixel focal plane in both front- and back-illuminated configurations. Data were acquired on several known asteroids via a small scale search at opposition as well as via observations directed at known objects. In May 1993 a camera system based on the next generation 1024X1024 front illuminated pixel CCD was tested at the ETS. Several known objects were observed including 114 Kassandra as shown in Figure 12.

The system detection performance during these tests was quite good Figure 13 displays the detection performance for objects (stars) of known magnitude. Data from both front- and back-illuminated CCDs are included in the figure which shows the integrated signal as a function of the magnitude of the observed object for a given integration time. The dimmest catalogued object observed had a visual magnitude exceeding 20. This measurement validates the performance of the detector system for quite dim objects.

During the summer of 1995 the latest generation of CCD camera will be taken to the ETS and installed on a GEODSS 40-inch telescope for a series of tests related to the GEODSS Upgrade Program. These tests will employ a back-illuminated 1960X2560 pixel CCD in a step stare search mode. As an adjunct to the main tests, we plan to conduct a series of observations specifically tuned to determine the system performance for the detection of NEOs. These measurements will include demonstrations of the detection capability of the system as well as the acquisition of multi-frame data sets suitable for detection algorithm development. In addition we hope to conduct rudimentary operations of the system in the NEO search mode to gain experience with any operational issues that are involved.

Conclusions

DOD-developed Space Surveillance technology has been reviewed for its applicability to the detection of NEOs. Detection systems developed for the upgrade to the GEODSS system have been examined and found to

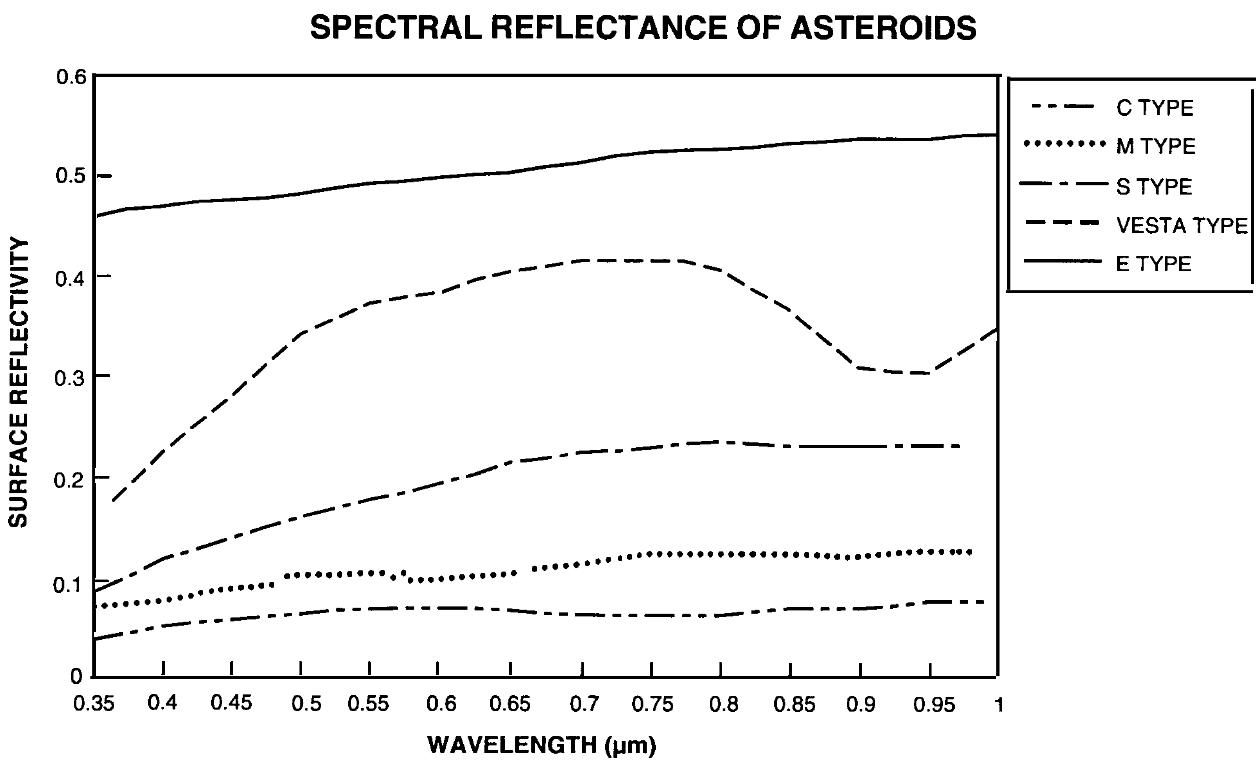


Figure 8. Spectral reflectance of asteroids (after Ref. 1).

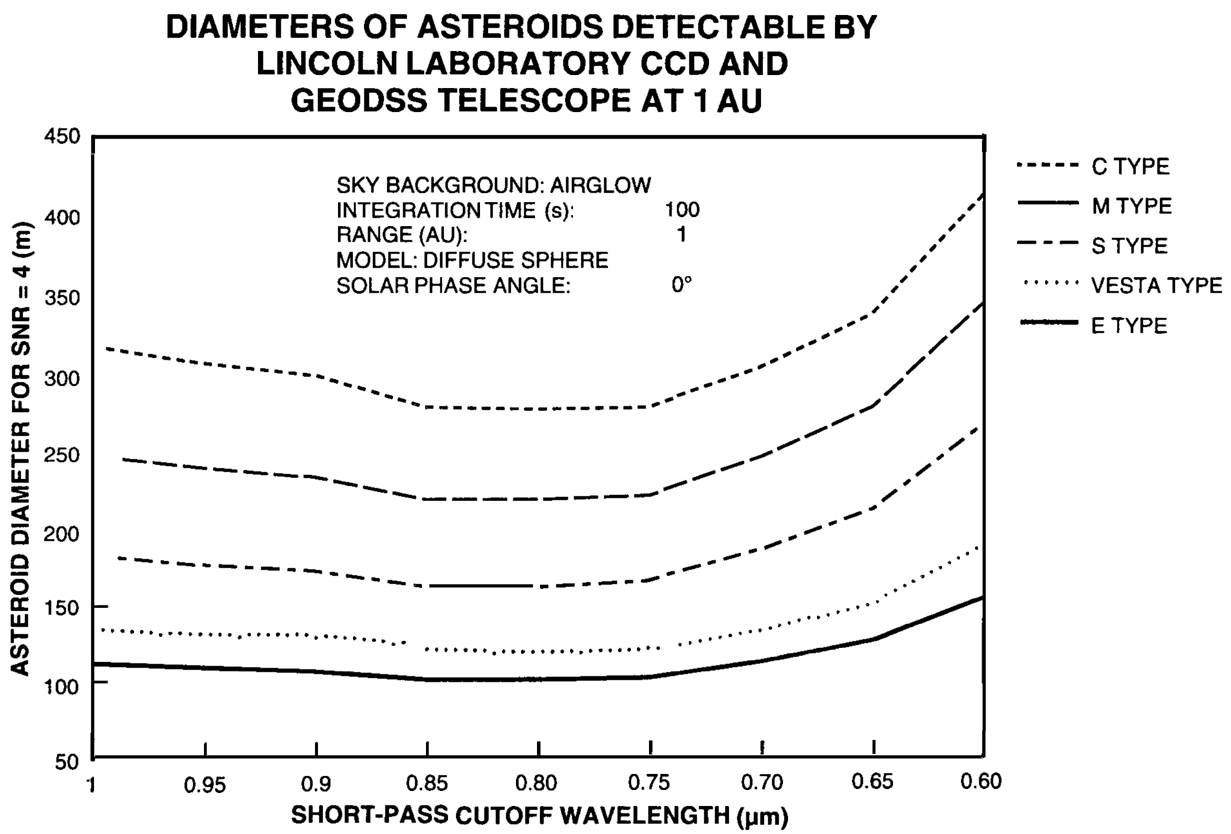


Figure 9. Minimum asteroid diameter detectable by GEODSS/CCD at 1 AU by spectral type of asteroid as a function of short pass cutoff filter wavelength.

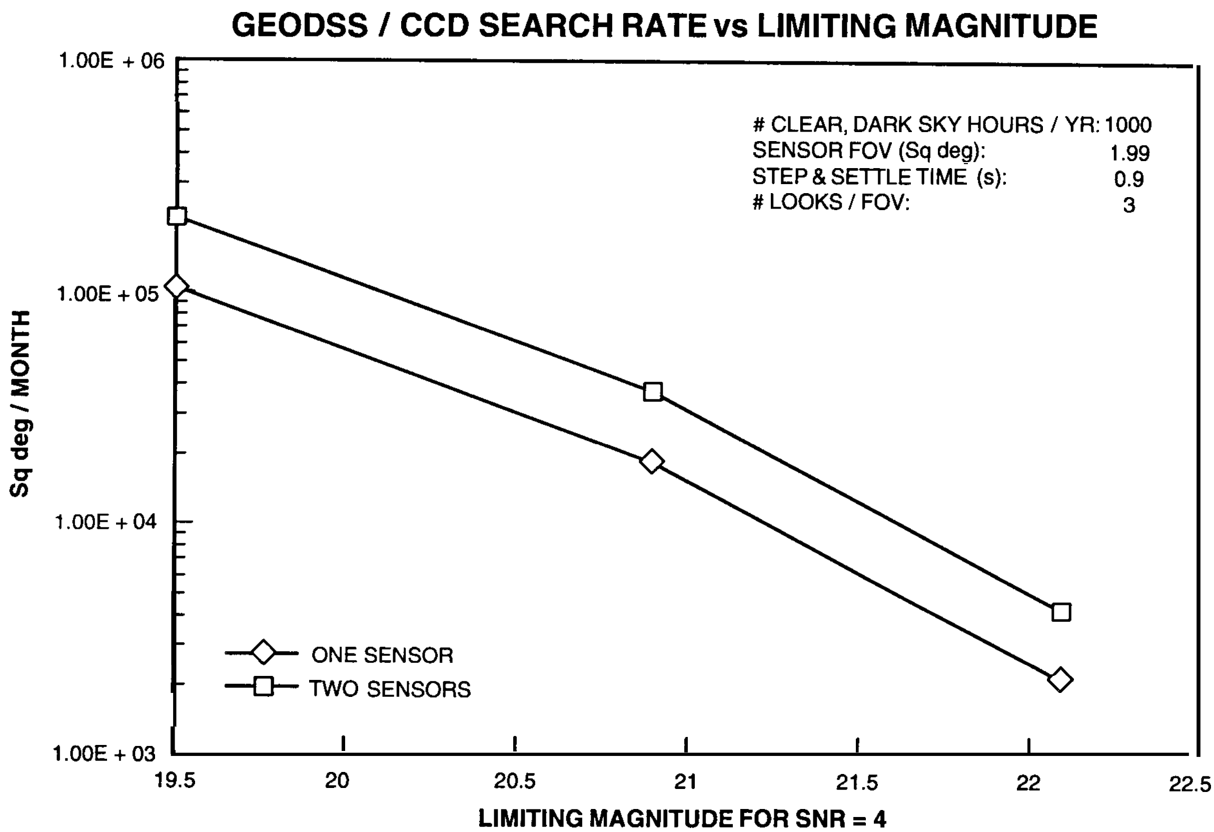
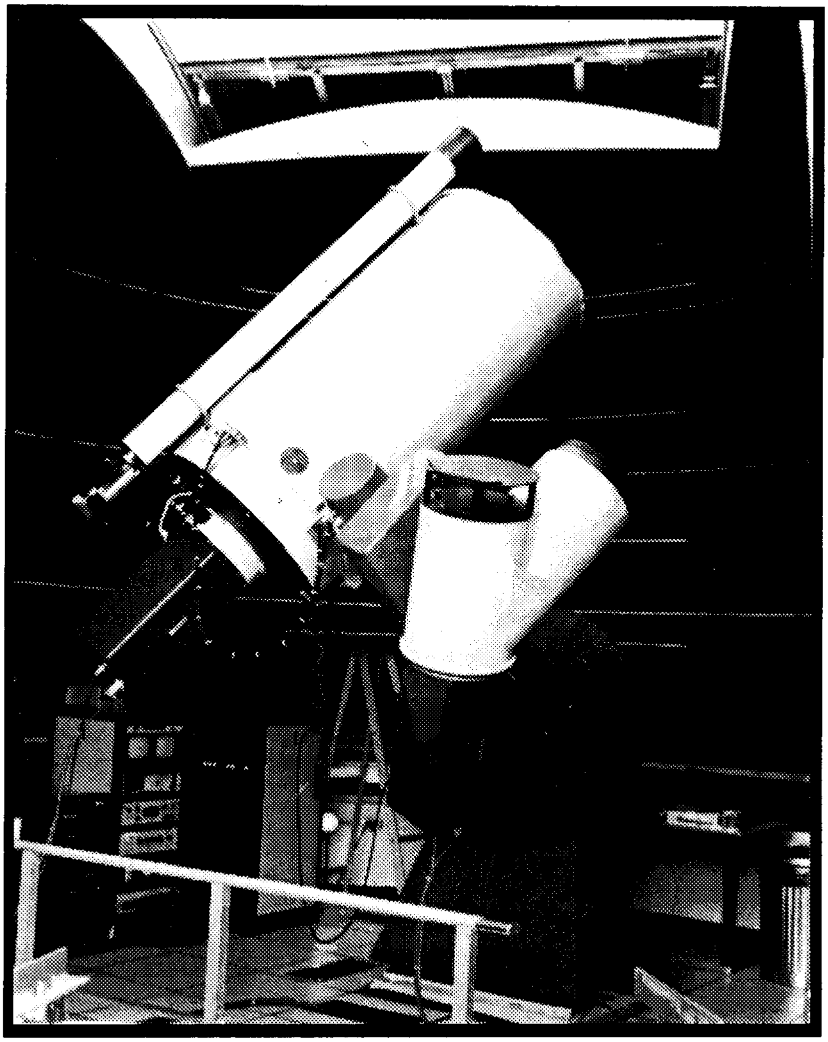


Figure 10. Search rate achievable by one or two GEODSS/CCD telescopes and a function of limiting magnitude.

ASTEROID DETECTION EXPERIMENT



31 INCH POLAR MOUNT CASSEGRAIN TELESCOPE AT LINCOLN EXPERIMENTAL TEST SITE

Figure 11. Experimental Test System telescope used during historical field tests including asteroid detection experiments.

DETECTION OF ASTEROID 114 KASSANDRA NEAR OMEGA NEBULA

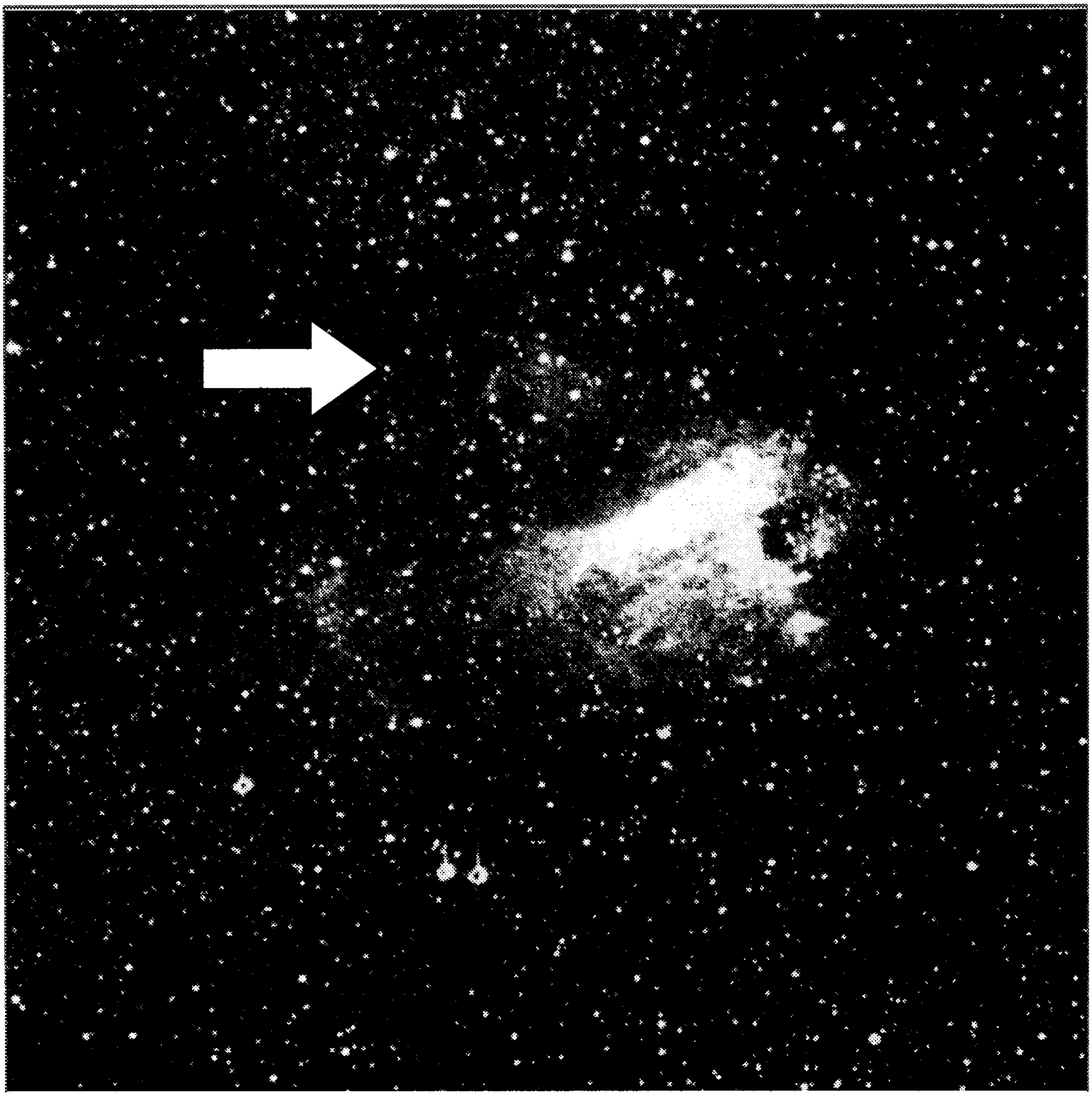


Figure 12. Detection of 114 Kassandra near the Omega Nebula

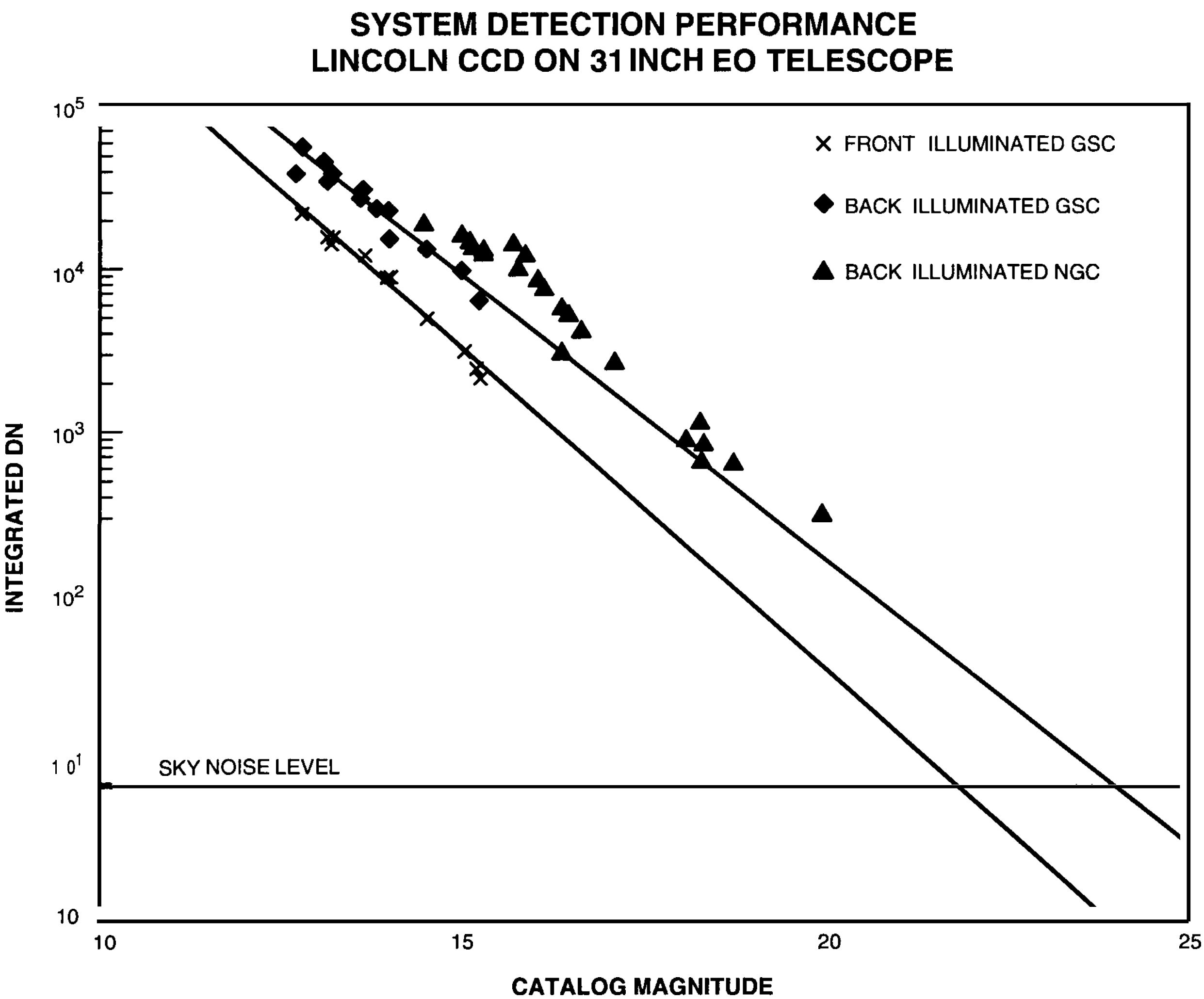


Figure 13. System detection performance achieved during historical field tests using the Lincoln CCD detector on the ETS 31" telescope.

provide detection performance using 1 meter telescopes which rivals the performance expected from the Spaceguard system which proposes using commercial CCD detectors on six 2.5 meter telescopes. A system of four upgraded GEODSS telescopes could search 6000 square degrees per month to a limiting magnitude of 22, which is the Spaceguard goal. Alternately, two upgraded GEODSS telescopes could search the equivalent of the entire sky once per month to a limiting visual magnitude exceeding 20.5.

Field test validating the performance of predecessor versions of the detections system have shown the expected performance on natural objects. A new series of field measurements are planned for the summer of 1995. The goal of the new series is to validate the performance of the system containing the latest version of the Lincoln developed CCD for NEO detection and to develop operational experience conducting NEO searches.

References

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